Abstract

In this paper we describe incorporating Einstein’s Special Theory of Relativity into an interactive computer game intended for learning and teaching purposes in Australian senior high school and tertiary education. The game, which is based on Asteroids, embeds either a classical or relativistic model of physics in the game environment such that players interact directly with the physics in the course of playing, and can observe and contrast their behaviour. The emphasis is on conceptual portrayal with 2D graphics, rather than immersive and realistic 3D visualisation. The key relativistic concepts of length contraction, time dilation, and mass dilation are each represented, as well as Doppler shifting of colour. We discuss design considerations and graphical devices for portraying these effects in the game, along with results and responses from user experiments.

Keywords—serious games, games to teach, physics, relativity, relativistic visualisation

1 Introduction

Albert Einstein’s Theory of Relativity [2] is one of the most important results of modern physics, and today is part of everyday science and technology. Relativity is a fascinating but also widely regarded as a difficult topic in physics, largely due to difficult mathematical formalisms and unexpected and counterintuitive phenomena. Concerned as it is with the behaviour of objects travelling at near to light speed and the nature of space and gravity, relativity is also impossible to directly observe or experience in a practical sense.

Computer-generated worlds represent one method of enabling more “hands-on” learning with such difficult concepts. Environments simulated on computers can be programmed to behave according to the laws of classical mechanics, or other rules [13], and can allow users to experience and explore domains that are outside of their everyday purview. This naturally leads to computer games, which often place players in such environments (such as a fantasy or science-fiction setting), and/or grant them powerful or superhuman abilities. Even with games that are grounded in real-world activities, such as realistic first-person shooter or driving games, the flexibility of the computer-simulated world can allow for such unlikely features as time manipulation (e.g. “slow-mo” or rewinding gameplay).

Simulated environments can be useful to enhance teaching and learning in domains such as physics. In [9], Price describes using commercial game technologies to create interactive physics experiments for secondary school students. In addition, there has in recent times been a lot of interest in how computer games themselves teach and convey knowledge [4]. Well-designed computer games provide motivation and challenge for players to improve, which promotes players’ learning of game actions through reinforcement and practical use.

An example of an educational game that brings all these aspects together is Supercharged! [13], which was designed for teaching electromagnetism to American middle-school students. The game visualises magnetic field lines and demonstrates how charged particles interact; the gameplay is built around the Maxwellian principles of electrostatics, as opposed to Newtonian physics. In a study of learning of 8th-grade students, the researchers found the game helped learners build stronger and more practical intuitions for electromagnetic concepts than traditional classroom instruction.

This paper follows up our earlier report on developing a computer game that incorporates features of relativistic physics [1]. Along the lines of Supercharged!, these features are embedded in the gameplay design so that players interact with them directly. The relativistic features in the game also map to the learning outcomes of the Higher School Certificate (HSC) physics course for Australian senior high school students (Years 11 and 12). Thus, the game should prove valuable for teaching purposes in Yr11-12 and tertiary physics courses. We have conducted user studies to evaluate the game and present a summary of the outcomes at the end of this paper.

2 Special relativity and computers

This article focuses on the part of the Theory of Relativity [2] known as Special Relativity, which is concerned
with the description of objects and events travelling at close to the speed of light. Einstein used the following two postulates to formulate special relativity:

1. The laws of physics are the same to all inertial observers.
2. The speed of light is the same to all inertial observers.

For an observer in constant motion relative to some frame of reference, light will always appear to travel at the same speed (i.e. distance over time), irrespective of relative velocities of light sources. This leads to the principal effects described by relativity of space contraction (measurements of length of a relatively moving object will be shorter than when at rest) and time dilation (time passes more slowly for an object in relative motion than at rest). In addition, as the energy content of a moving object increases, due to the equivalence of mass and energy given by \( E = mc^2 \) it is sometimes said that the moving object increases in mass [5].

### 2.1 Special relativistic visualisation

The short story *Mr Tompkins in Wonderland* by physicist George Gamow [3] describes the exploration of a world where the speed of light is reduced to 30mph. This causes the effects of special relativity to become apparent in everyday activities, such as where the title character observes Lorentz length-contraction of a passing bicyclist. In this way, Gamow presents an overview of relativity’s features in an accessible and illustrative way for newcomers. This story also introduced the novel device of ‘slow light’, which embodies an elegant way to illustrate relativity using more accessible and familiar scenarios. Changing the speed of light acts like a scaling; it does not change the physics [10].

In recent times, computers have enabled us to simulate relativistic effects in virtual realities, and the latest such simulations used in educational settings enable interactive 3D flights at speeds close to a virtual speed of light [11][7]. Following results first given by Penrose [8] and Terrell [14] in the late 50’s, much attention has been paid to the question of what would really be seen by an observer or camera in such situations. It turns out other effects conspire to dominate the visual appearance of objects [10], and ‘pure’ Lorentz length-contraction as described by Gamow is generally invisible [12].

The game described in this paper takes a different approach to the above-mentioned simulations, as it uses 2D graphics and more conceptual representations of the relativistic effects. The focus instead is on presenting principal relativistic effects in a simple, stylised or literal manner, and the use of game design elements to provide structure and motivation for the experience.

### 3 ‘Relativistic Asteroids’ game design

Our game design is based on the classic arcade game *Asteroids* [15]. In this two-dimensional game, the player controls a wedge-shaped spaceship, manoeuvring around the screen. The objective is to earn points by shooting and destroying drifting asteroids, which split into smaller fragments when shot, while avoiding collisions. When the player has cleared all the asteroids from the screen, a new batch is generated, and the game continues until the player has expended all their lives.

The game is implemented in C++ and uses the Microsoft DirectX 9.0c API for graphics operations. It can be downloaded from http://csusap.csu.edu.au/ dcarr/

Our Relativistic Asteroids game can be played in a number of different modes, which revolve around the two opposing models of physics: classical (Newtonian) mechanics (Figure 1), and relativistic mechanics (Figure 2). The game can be played under either physics model, and the differences in effect compared. We employ the ‘slow light’ mechanic to scale the simulated speed of light to a value easily attainable by game objects, such that relativistic effects will readily enter into the gameplay. (With an 800x600 or 1024x768-pixel game screen, this equates to an on-screen object speed of 120 pixels per second, styled in-game as 120 metres/sec.)

The primary player controls consist of left and right ship rotation, forward thrust, and a fire button. Ancillary controls for extra gameplay functions are an afterburner for amplified thrust, and a shield for temporary invulnerability. The player views the action from a third-person perspective, with the ship and other objects moving around the on-screen playing area. In terms of relativistic frames of reference, the player’s point of view can be thought to reside in an external reference frame at rest with respect to the playing area, to which the game objects are in states of relative motion. This design was initially chosen in mind for incorporating mass dilation as a gameplay element, which has so far not been treated in simulations previously mentioned.

Graphics are rendered as simple line drawings, to keep the focus on the effects. The following sections describe the relativistic effects portrayed in the game.

#### 3.1 Length contraction

Game objects (asteroids, projectiles and the player’s ship) travelling in the game environment at close to the in-game speed of light exhibit Lorentz length-contraction. This is depicted literally, so that the objects appear compressed along their direction of travel. This is not totally realistic, but can be thought of as an approximation of the
Figure 1: A game of Asteroids being played under the Classical mechanics model, which behaves in the expected way.

Figure 2: Under the Relativistic mechanics model, game objects exhibit relativistic effects visually (contraction and colour change) and in their behaviour (inertial mass and time-based functions).
special case where pure Lorentz contraction is visible to an observer [12].

### 3.2 Mass dilation

Asteroids and the player’s ship have speed-dependent mass, which increases as they approach the speed of light. This is primarily communicated through the player’s spaceship, which behaves as an inertial body. In order to move in a direction, the player must orient the ship and apply thrust, which applies a force to accelerate the ship. At high speeds, the player must take into effect the increased mass of the ship when attempting to effect direction changes. Mass dilation also means that light speed is an ultimate ‘speed limit’ for all in-game objects.

In order to assist communication of this effect, the on-screen ‘heads-up display’ (HUD) text also reads out the current mass dilation as a factor of the ship’s rest mass. In addition, graphical effects have been trialled to try to convey visually an idea of a fast-moving object’s increased mass (Figure 3). In earlier versions of the game this involved a ‘trail’ effect, which drew a series of fading after-images behind the objects [1]. In the current version of the software, an effect has been programmed which draws fast-moving objects with a proportionally thicker outline.

### 3.3 Time dilation

Time dilation affects certain time-dependent functions of the player’s ship, including its turning rate, and the lifetime of projectiles. Time dilation is also depicted in special (randomly-generated) ‘time bomb’ asteroid objects. These are asteroids rendered with a red outline, and displaying a numeric timer counting down in seconds. When the timer reaches zero, the asteroid explodes, sending projectiles over a short-range that can destroy other asteroids and the player’s ship. The timer on these asteroids is affected by time dilation from motion.

### 3.4 Body-to-body collisions

Asteroids in our game have been programmed so they can collide and bounce off one another. These are resolved as elastic collisions, but the speed-dependent masses and shapes of the objects require special consideration. Collisions are calculated by transforming colliding object pairs into a centre-of-inertial mass frame, to reduce the change of velocity problem to one dimension [6]. This generally results in relativistic collision outcomes that are different to the classical case, although the difference is often too subtle to be noticeable visually (apart from fast-moving small objects imparting a disproportionate impulse to larger, more massive ones).

### 3.5 Redshift and blueshift

A graphical effect to loosely imitate the Doppler shift of the wavelength of visible light is included in the most recent version of the game. Fast-moving objects have their colours altered based on their velocity and distance from the centre of the screen. Objects moving toward the centre of the screen are treated as approaching and have their colour shifted to blue; objects travelling away from the centre are treated as receding, and are tinted red. Although in no way a physically accurate interpretation of optical effects, it gives a visually pleasing representation.

### 3.6 Game modes

The game can be played in a ‘pure’ classical physics mode, or a ‘pure’ relativistic mode with a fixed ‘slow light’ speed. A ‘challenge’ mode was also designed that combines the two: beginning with classical physics, then transitioning to relativistic physics with decreasing light speed over successive levels.

Initial feedback also lead to the addition of a ‘practise’ relativistic mode, in which the player’s ship is invincible, and simply bounces off asteroids rather than being destroyed by them. This enables players to experiment more freely with the relativistic physics, without the inconvenience of crashing and dying all the time. To ease players into dealing with the length contraction (which can make it difficult to tell the direction of the spaceship), an arrow device was also added for this mode to make the ship’s heading explicit (Figure 3).

### 4 User experiments

The game was evaluated in trial user studies conducted in 2008 and 2009. The trials involved classes of Yr11-12 students studying HSC physics (n=41) at local high schools, and student and staff volunteers at CSU (n=26). Participants were issued questionnaires before and after playing the game, to measure their understanding of relativity and collect impressions and evaluations, and non-identifying demographics. Each trial session took roughly one hour to complete.

For the studies at CSU, volunteers who had little to no prior physics background were recruited to attend sessions conducted in CSU’s Games Technology Laboratory. Each participant group was given a verbal overview by the researcher, and led through playing the game in the classical and relativistic mechanics game modes and completing the relevant questionnaires.

The studies with HSC students were conducted in physics classes at several local high schools, with the supervision and cooperation of physics teachers, who were able to incorporate the game into a lesson and direct students through the activity. For some student classes this
was a first introduction to relativity, while it was a revision activity for others that had already studied the topic.

Experimental results showed that there was a measurable improvement in comprehension among the learning cohorts. These outcomes will be fully discussed in a future paper. The discussion below will focus on subjective user responses and evaluations about the design of the game.

4.1 Evaluations

Participants were asked to evaluate the game by responding to a set of attitudinal questions on a 5-point Likert scale (from Strongly Agree to Strongly Disagree). Participants overall rated the game favourably, regarding it as fun (87% agree or strongly agree), and that it made the topic more entertaining and motivating to learn (82%).

Divided into cohorts that had and had not previously studied the topic, those new to the topic felt more strongly that they had learnt from the activity (85% versus 64% disagreement with a negatively-worded statement); however, respondents experienced in the topic felt more that the game clearly demonstrated the differences between classical and relativistic physics (82% versus 72% agreement).

There was strong correlation between the evaluations, user comments and learning result, regarding the specific effectiveness of the portrayal of the principal relativistic effects. The length contraction and mass dilation effects were both deemed effective, but time dilation was particularly singled out as needing to be more pronounced.

4.2 User responses and discussion

In open ended questions, responses frequently indicated that the best features of the game were the graphical portrayal of physics, especially seeing the colour shift and “changing shape” (length contraction). At the same time, the game graphics were also cited as an area that could be improved; but some responses also indicated that the simplicity of the game was an advantage. Other suggestions for general improvement mentioned the addition of sound effects, better game variety, and inclusion of mechanisms to experience other related physics effects (switching the frame of reference to be relative to the spaceship, and the relativity of simultaneity).

In general comments, many respondents expressed appreciation of the game activity (e.g. “great fun”). Other studies have reported how interactive technologies can help learners build more intuitive explanations [13] or make physics topics less abstract [7], and this was also reflected in comments we received, such as “I think it could be of great practical use in school to learn about what I find an off the planet and dry subject” and “putting theory into practice”. One teacher also gave detailed feedback, saying that she felt the game was a “wonderful resource that is... a bit different and worth exploring” and that she would certainly use it to support classroom teaching: “I would [introduce it] as a resource [and] let them take it home to play”.

A few comments suggested that “the physics concepts need to be more reinforced...” and “the game is only really effective as a learning tool when the player has someone nearby to explain what is happening”. One particularly astute student comment was that “the physics principles from this game are learnt via observation skills...”, and along with other comments, suggested that an in-depth information section, audio commentary, and/or guided gameplay would help support communication of the relativistic effects.

A combination of observation and survey data showed that of those subjects who were HSC students, age, gender and prior gaming experience had no significant impact on their experiences with the game in the experiment. However, in the university volunteer cohort, a few subjects in particular had difficulty grasping how to control the game, perceiving a discontinuity between the mapping of the controls and orientation of the on-screen spaceship.

Observation revealed an issue with the combination of conceptual with representative visual effects. When the colour-changing of objects was explained as a representation of Doppler shift, one participant asked if the expanded object outline (which appears ‘glowing’) was also a relativistic effect. This highlights that the combination of graphics effects for different purposes needs to be carefully considered to avoid confusion.
Conclusions

We have presented our game design that incorporates relativistic physics principles into the game mechanics, and discussed user reactions to it from trials. The software utilises the challenging construct of a game to motivate players to persevere to build up their understanding of its rules, but also serves as a demonstration tool that can be used with instruction as an effective introduction for new learners.

The game proved effective at communicating concepts of length contraction and mass dilation, as well as Doppler shifting of colour - components which were given strong visual presence - but it was less effective at communicating time dilation, despite its affect on several in-game elements. Players needed more time to detect and understand this subtle effect, or required something to direct their attention. This, and other features such as frame switching, represent areas for possible future improvement.

The goal is a software that can stand on its own to popularise Einstein’s physics with the general public as a leisure game, while also providing a platform to enhance teaching. Considerations for the former are the need for a structured, self-directed gameplay delivering knowledge, and for the latter is the need to facilitate demonstration and to make the game accessible for ‘digital immigrants’.

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References


